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A SUPPLEMENTARY STUDY OF THE LOCOMOTIVE FRONT END BY MEANS OF TESTS ON A FRONT-END MODEL

BY

EVERETT G. YOUNG



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A SUPPLEMENTARY STUDY OF THE LOCOMOTIVE FRONT END BY MEANS OF TESTS ON A FRONT-END MODEL

I. INTRODUCTION

1. *Previous Investigation.*—Bulletin 256 of the University of Illinois Engineering Experiment Station* records a series of tests made on a quarter-scale model of a locomotive front end. In that bulletin the general problems of front-end design and performance were considered, and the data from some four thousand tests were analyzed, in an effort to clarify the laws of front-end action as governed by the arrangement of the various parts and by the physical conditions of operation, such as steam and gas temperature, pulsation, humidity, resistance to the flow of air or gas, etc. It is the purpose of the present bulletin to supplement the previous publication by recording the results of further examination of certain general relations, and of tests made on the same model designed to learn the relative merits of certain modifications of the conventional front end which are now coming into use.

2. *Locomotive Front End.*—The “front end” of a locomotive consists of all those parts comprised in the extension of the boiler shell forward from the tube sheet, including the shell or smokebox, the stack, the nozzle stand and exhaust tip or nozzle, usually an arrangement of baffle plates and netting, and certain other parts, such as the superheater header and steam pipes, which are located for convenience in the front end but which are not directly concerned with its action. In Fig. 1 is shown the front-end arrangement of the United States Railway Administration heavy mikado-type locomotive, commonly designated as the 2-8-2-B, with the principal parts named. The model used in these and the previous tests is based on this arrangement. The locomotive front end has for its sole function the drawing of air for combustion into the ash pan and through the grate and fuel bed, and, after a certain portion of this air has served to make combustion possible, the moving of the remainder mixed with the products of combustion through the tubes, and, finally, the ejection of it from the stack. This function is performed by reason of the discharge of

*“A Study of the Locomotive Front End, Including Tests on a Front-End Model,” by Everett G. Young. 1933.

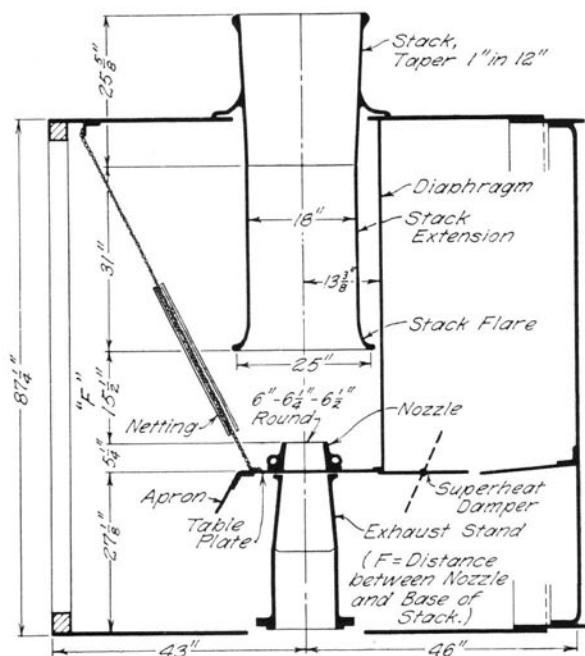


FIG. 1. FRONT-END ARRANGEMENT OF U.S.R.A. 2-8-2-B LOCOMOTIVE

the exhaust steam into the front end through the nozzle at a considerable velocity, and the consequent mixing and "surface" friction action on the surrounding air and gas, by which the latter are drawn along and ejected with the steam from the stack.

3. *Scope of This Study.*—In the present report, special attention is paid to the results secured by altering or eliminating the netting and baffle plate arrangement, the consequent possible variation in the positions of the nozzle, the form of the base or flare of the stack, the use of an entirely different type of arrangement (the gyratory spark arrester) which offers much promise, and the effect of moving the nozzle away from the traditional position on the axis of the stack.

4. *Results of Tests.*—The results of the investigation are not such as lend themselves to a summary concise enough for the present introduction. The reader is directed to Chapter IV as a general recapitulation. In the previous bulletin it was pointed out that the principal operating condition affecting the front-end performance was the resistance of the grates and fuel bed to the entry of air into the firebox;

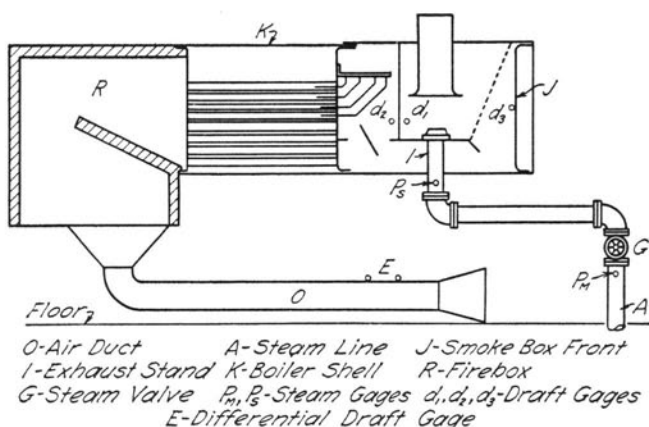


FIG. 2. UNIVERSITY OF ILLINOIS FRONT-END MODEL

in the present report it will be shown that the reduction of the resistance to the passage of gas through the front end also materially improves the performance. In the previous report it was shown that the distance from the top of the nozzle to the top of the stack was the most important dimension governing the performance aside from the nozzle diameter, unless either the stack or the nozzle or their mutual relation is very badly designed; in the present study the importance of this dimension is further demonstrated. Similarly, it was previously shown that changes in the height and form of the stack base or flare had only trifling effects on the performance, and further evidence of this fact is given in the following pages.

5. *Acknowledgment.*—This research has been a part of the work of the Engineering Experiment Station of the University of Illinois, of which DEAN M. L. ENGER is the director, and of the Department of Railway Engineering, of which PROF. EDWARD C. SCHMIDT is the head.

II. LABORATORY INVESTIGATION

6. *Front-End Model.*—As has been previously stated, the model used in these tests and in those of the previous investigation is a quarter-scale reproduction of all of the essential parts of the front end shown in Fig. 1. The general arrangement of the model is shown in Fig. 2. Access to the interior of the front end is obtained by removing the plates at either side of the "boiler head," and, as a result of the auxiliary apparatus available, an almost unlimited num-

ber of internal arrangements becomes possible. The measurement of the following quantities is provided for:

The pressure of the steam in the throat of the jet corresponding to the exhaust pressure of the locomotive (P_s), in lb. per sq. in.

The weight of air flowing through the model in pounds per hour, from the indications of a calibrated differential draft gauge (W_a).

The draft at any point in the front end; in particular at two points corresponding to the standard location of the draft gauges for a locomotive test as shown in the A. S. M. E. test code, and at one additional position in the center of the "boiler head," or front plate.

The temperature of the air entering the model, and the humidity of the air as determined by wet-and-dry-bulb thermometers.

The pressure of steam in the main from the power plant, this being used merely as an index of the comparability of tests run at different times.

The barometer indication.

The model was originally equipped with a special rotating steam valve, by means of which the puffing action of a locomotive could be simulated, but tests in the earlier investigation showed that the operation of this valve and the delivery of a pulsating flow of steam had no effect on the results upon which essential conclusions were based. The pulsator was consequently eliminated. The use of a steam flow-meter for the first 2300 determinations in the original investigation established satisfactorily the steam discharge for each nozzle used in the earlier studies, and accurate methods of estimating the flow from the new nozzles used in the present study. Many thousands of steam temperature measurements made in the earlier stages indicated the range and effects to be expected and were unnecessary in the later tests. In the earlier bulletin it was shown that comparisons between tests made with atmospheric air were as valid as those between tests made with hot combustion gases, and the procedure in the present research was simplified by not using the heaters.

7. Front-End Arrangements Used.—The nozzles used in these tests are shown in Fig. 3. It was originally intended to use but three, all of which had been thoroughly tried out in the main investigation. These three were the 1 $\frac{5}{8}$ Y, a plain round nozzle of a size appropriate for the prototype locomotive, the 1 $\frac{5}{8}$ L, similar but lower, and the

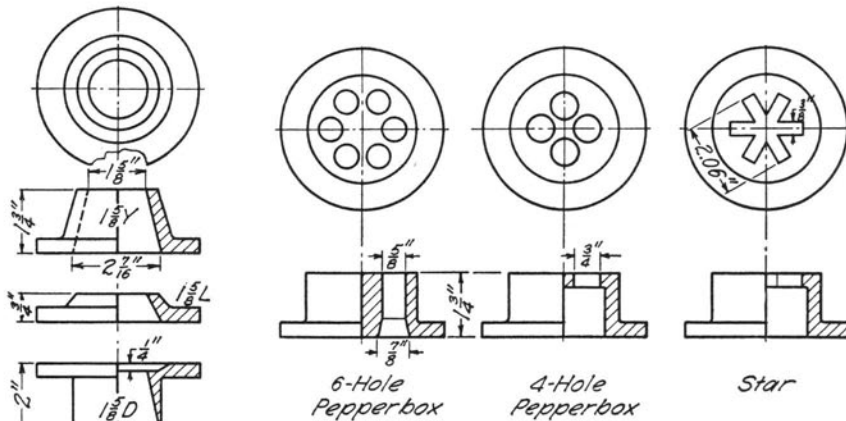


FIG. 3. NOZZLES USED IN TESTS

4-hole pepperbox, a nozzle which had commended itself under all conditions in the earlier studies. The 6-hole pepperbox, the $1\frac{5}{8}D$, and the star nozzle were added during the work of the present investigation, for the purpose of extending the range of conclusions relative to multiple openings, increase in the distance "F" from the top of the nozzle to the base of the stack, and special nozzle shapes. The No. 4 stack of the earlier research was taken as standard; and, with the regular small flare, it is herein designated as 4-0-S; when provided with a 2-inch cylindrical extension it is called 4-2-S, etc. Three other stack flares or bases were used, designated as Nos. 8, 9, and L, all of which are illustrated and dimensioned in Fig. 4.

The general plan of the present studies covers five groups of runs:

(a) A series of tests to determine the effect of piecemeal removal of the plates placed in the front end to control the flow of gas, since these plates add materially to the resistance of the path.

(b) A series of tests to determine the effect of varying the height of the nozzle (raising it by rings), and the various forms of stack flares, the front-end plates being all removed, and the nozzle lowered as far as the construction of the model would permit.

(c) A series of tests to determine the effect of placing a cylinder of netting around the base of the stack, the long conical flare designated as No. 8 (Fig. 4F), being used.

(d) A series of tests of a gyratory spark arrester of the type of the "Cyclone" arrester now being marketed, to find the relations between the resistance to air flow for the arrester, and for the conventional and "empty" front ends, respectively.

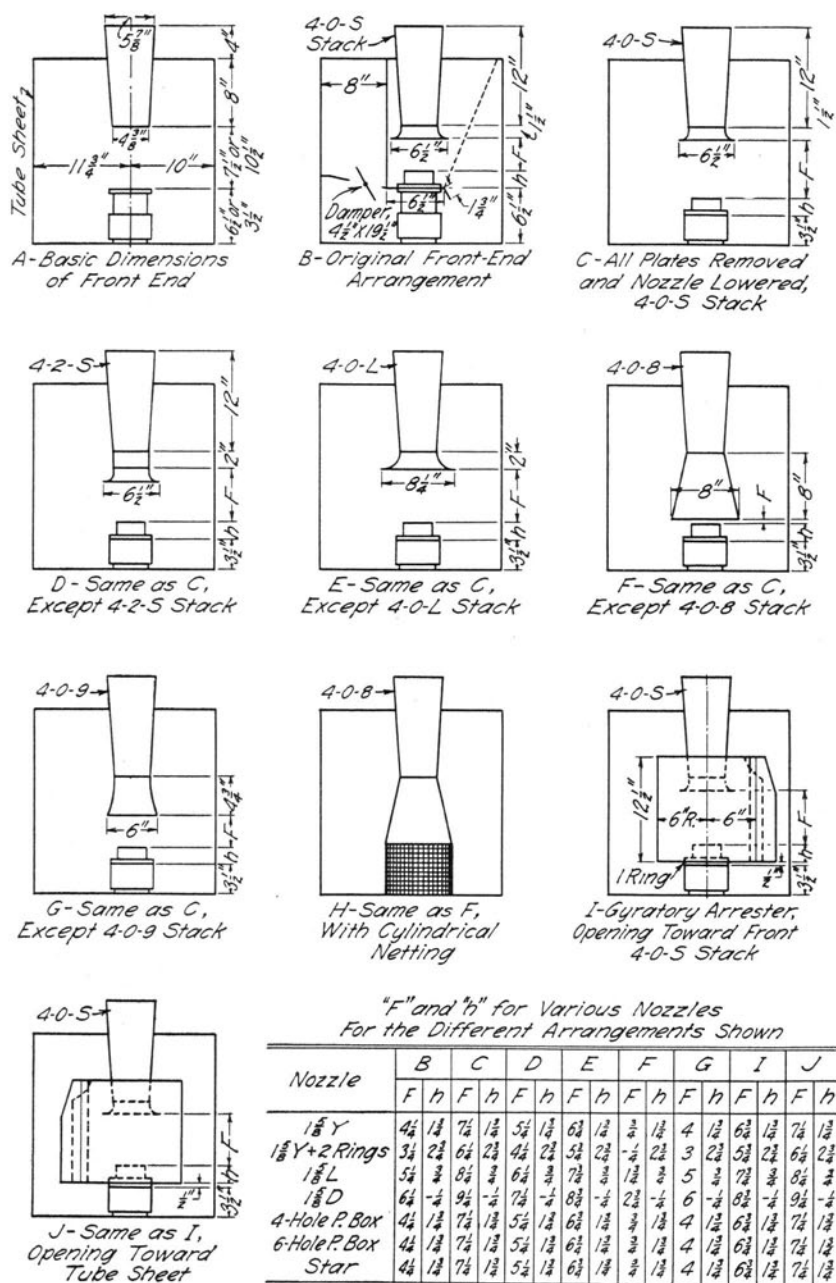


FIG. 4. FRONT-END ARRANGEMENTS TESTED

(e) A series of tests with the normal stack and lowered nozzle to evaluate the effect of moving the center of the nozzle relative to the center of the stack.

The table in Appendix A shows the distribution of the 800 determinations among the 60 front-end arrangements tried.

8. *Test Procedure.*—After the desired front-end arrangement had been set up, and steam run through the model until an approximate temperature equilibrium was reached, a series of jet pressures (usually five) was secured by adjusting the main steam valve. For each pressure, some minutes having been allowed for readings to become constant, the pressure, two air temperatures, two or three drafts, and the differential draft gauge reading indicating air flow were recorded. The set of data corresponding to a given pressure is herein called a "determination"; a group of determinations made consecutively with the same front-end arrangement and without interruption is called a "run". Preparing the data for presentation consisted in changing the differential draft gauge readings by means of a calibration into air flow in pounds per hour, and correcting this figure to correspond with the weight of air represented by the same volume at a temperature of 75 deg. F. and a pressure of 29.40 inches of mercury. A humidity correction was also considered, but was found so small as to be of no practical significance.

9. *Method of Presenting Data.*—For a given nozzle and front-end arrangement the principal operating variables to be considered are:

The exhaust jet pressure, which is fixed at the will of the operator,
 P_s pounds per square inch.

The rate of steam flow, dependent upon the nozzle used and the steam jet pressure,* W_s pounds per hour.

The draft in the front end, d inches of water.

The flow of air, corrected for atmospheric conditions, W_a pounds per hour.

A measure of efficiency.

Where the performance of nozzles with the same or varying front-end arrangements is to be compared, P_s , W_s and W_a may be related as the three projections of a curve in space, as shown in Fig. 5a. The actual space curve is shown in Fig. 5d. Where various front-end

*It is of course theoretically true that the variation in the vacuum in the front end for different arrangements would result in a variation in the flow for the same nozzle at the same pressure. It was found in the first investigation, however, that unless excessive differences in vacuum were obtained in the front end (as by making large variations in the choke opening, or resistance of the duct through which air was delivered to the model) the steam flow was not measurably affected by any element of the front-end arrangement.

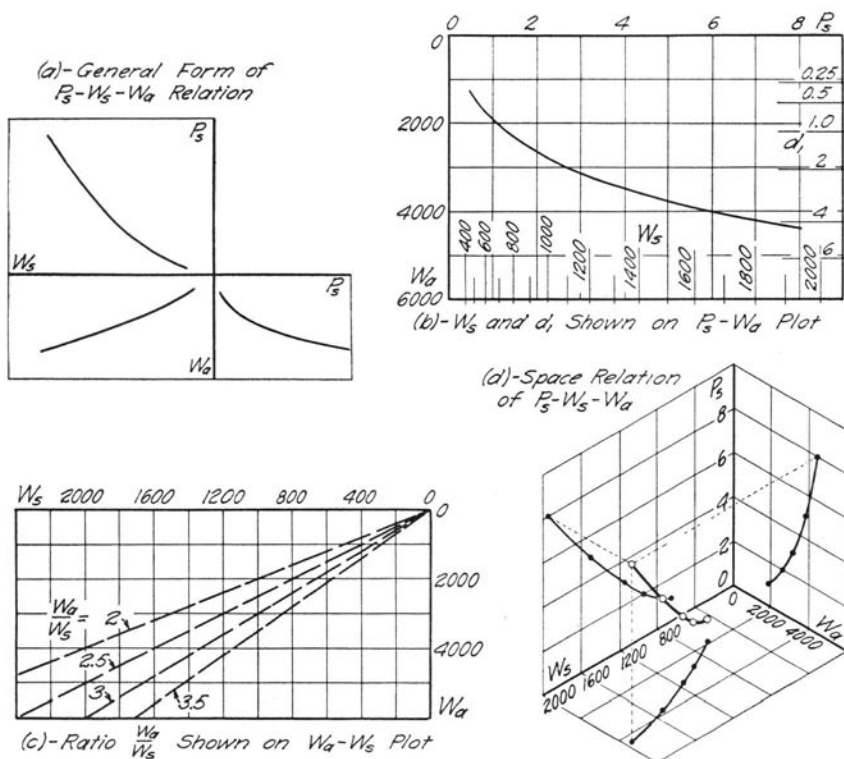


FIG. 5. METHODS OF PRESENTING TEST DATA

arrangements using the same nozzle are compared, the relation between P_s and W_a , one of the three parts of the complete plot of Fig. 5a, gives all the information needed. For any given front-end arrangement, there is found to be a fixed relation between the draft and the air flow which is independent of the nozzle used, and if information as to the draft is needed an unequal-parts scale in terms of draft may be laid off parallel to the W_a scale in Fig. 5b. When the P_s - W_a relation alone is used, since P_s and W_s are in fixed relation for a given nozzle, an unequal-parts scale showing the steam flow may be laid off parallel to the pressure scale. This is also illustrated in Fig. 5b. The most practical measure of efficiency is the relation between the flow of air and the flow of steam. The relative merits of various nozzles or stack arrangements are emphasized by drawing in the W_s - W_a relation lines of constant values of the ratio W_a/W_s , as in Fig. 5c. In the present study the P_s - W_a plot is mainly used, as the

majority of the comparisons are those of the results of changes in arrangement, leaving the nozzle unchanged. The reason for the non-use of draft as a basis of comparison is that draft is not a measure of front-end performance except under conditions where it is certain that there is no variation in the resistance of the path of the air. Where this resistance does vary, the draft readings give contradictory indications as to the effectiveness of the front-end devices.*

III. RESULTS OF TESTS

(A) Effect of Reducing Front-End Resistance

10. *Fundamental Operating Principles.*—Two fundamental operating principles were developed in the previous investigation; these were not new, but the nature and arrangement of the tests brought out their implications clearly. From the fact that the *velocity* of steam discharged had an effect on the air flow of importance substantially equal to that of the *rate* or quantity of discharge, the well-known fact results that reducing the nozzle opening improves steaming, that is, for the same discharge of steam in a given time more air is drawn through the fire, at the expense, of course, of increased exhaust pressure. Consequently, if a certain nozzle and front-end arrangement result in the drawing of sufficient air for satisfactory steaming (that is, a sufficiently large W_a/W_s ratio), any improvement in the nozzle or front-end arrangement in general will result in the moving of more air for the same amount of steam. This in turn makes it possible to draw the smaller amount of air actually required with a larger nozzle opening, which means the obtaining of sufficient air with a lower back pressure. The second principle of operation relates to the resistance to the passage of the gases. It was found that for a given steam rate and velocity of discharge (that is, a given nozzle and pressure), a decrease in the resistance resulted in a *larger* amount of air being moved with a *reduced draft*, and vice versa.

11. *Reducing Front-End Resistance.*—It seemed apparent that the second principle stated in Section 10 would point to an improvement in performance if the resistance to the passage of the air through the front end were also reduced. The changes resulting were considerable, but much smaller than those which occurred as a result of choking or relieving the air duct into the firebox, the latter decreasing the resistances of ashpan, grate and firebed. In addition to its main

*This is discussed at length in Bulletin 256.

function of supporting and urging combustion, by drawing air through the fire, the front end must take care of the sparks from the fire. These must be discharged from the stack and not allowed to collect in the smokebox, and they must be reduced to such a size that they will not carry sufficient heat to ignite anything with which they come into contact after they have been discharged. The first requirement seems to make it necessary that the gases travel at high velocity through restricted openings in the front end in order that the cinders should be carried with them, and the second that the cinders be thrown with great force against a netting until they are broken up to such a degree as to pass through it. The usual front-end arrangement as shown in Fig. 1 makes it necessary for all of the gas coming through the tubes above the level of the table plate to have its direction of flow varied through five right angles, or 450 degrees, in place of the single 90-degree change of direction actually required to eject it. Much attention has recently been paid to the simplification of the front end, and it was planned to measure the effect of this simplification by removing the baffles or barriers in the smokebox one at a time, assuming that the spark problem might be otherwise solved.

12. *Tests with Reduced Front-End Resistance.*—With the normal or Master Mechanics' front end, a long series of tests was run with the 1 $\frac{5}{8}$ "Y nozzle, in order to find the effect of day-to-day variation, the validity of tests made under various weather conditions, etc. and to establish a norm of performance. After the superheater damper was taken out, it was found that the removal of this one partial barrier, not a very important one, since it lies almost parallel to the path of most of the gas flowing by it, produced no significant effect. Similarly, when the apron in addition was removed, there was insufficient difference to warrant plotting a different relation for the air flow from that given by the normal arrangement. When the netting as well was taken out, it was found that there began to be a fairly recognizable difference at all rates of steam flow except that corresponding to 1 lb. pressure, and this difference at the highest output rate was about 150 lb. of air per hour or 3.5 per cent. This was followed by the removal of the table plate without significantly different results, and finally by the removal of the diaphragm, from which another improvement in air flow could be seen, bringing the total gain up to 6 per cent over the performance of the original front end. Similar tests were run with the 1 $\frac{5}{8}$ "L and 4-hole pepperbox nozzles with similar results, the 1 $\frac{5}{8}$ "L showing slightly the largest gain of the three, but this

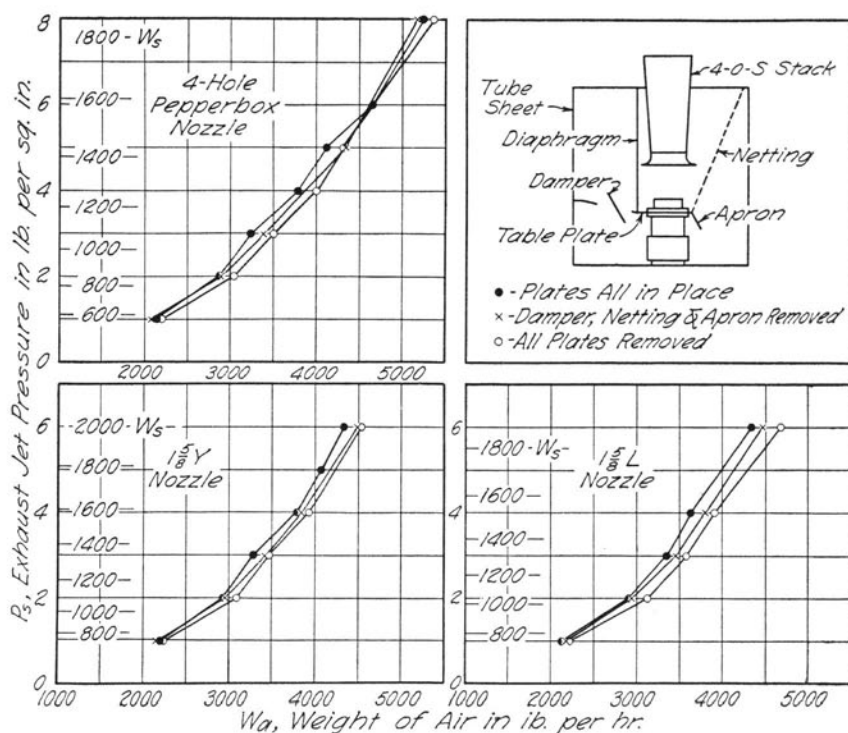


FIG. 6. EFFECT OF REDUCING FRONT-END RESISTANCE

was no more than about 7 or 8 per cent. The results of these tests are plotted in the three parts of Fig. 6, each part of the figure relating, respectively, to one of the three nozzles.

13. *Effect of Netting.*—The full gain developed by taking out all of the plates presumably cannot be realized on account of the necessity of finding some way of taking care of the sparks. The netting effect in the Master Mechanics' front end may be considered as evaluated in terms of air flow by the intermediate curves plotted in Fig. 6, since the effect of the apron and damper was too small to be separately determined. This netting effect was about three or four per cent, and the netting may be considered as responsible for about half of the total resistance effect of the various baffles, etc., in the front end. The areas of the various gas passages in the model as used in the Master Mechanics' form were as follows:

Tubes, 127 sq. in.

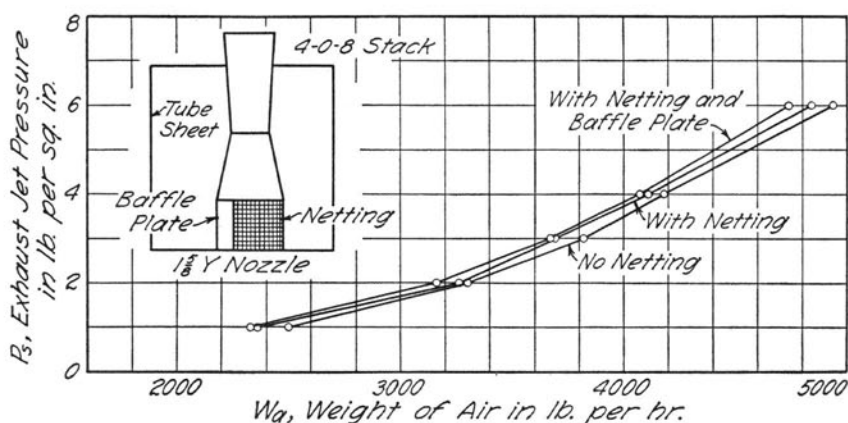


FIG. 7. EFFECT OF NETTING

Superheater damper opening, 76 sq. in.

Under table plate, 75 sq. in., deducting exhaust stand.

Under apron, 73 sq. in., not deducting exhaust stand.

Through netting, 81 sq. in., which was a net opening of 28 per cent of a total area of 290 sq. in.

The actual obstruction due to the netting was probably greater than that indicated by the area, since it is known that most of the air passes through a relatively small portion of the total area and there is very little movement around the edges.*

As a further means of evaluating netting effect, a series of tests was run with the 4-0-8 stack and the $1\frac{5}{8}$ Y nozzle (see Fig. 4H) after the latter had been lowered. In these tests a cylinder of netting was placed around the base of the stack. The area below the base of the stack without the netting is 150 sq. in.; with a netting of 40 per cent opening, this is reduced to 60 sq. in., and with a 66 per cent netting the air passage is 100 sq. in. It was found that the restriction to 100 sq. in. produced a negligible effect on the flow of air, while the restriction to 60 sq. in. produced a definite reduction of flow, as shown in Fig. 7. A further reduction was produced by covering the back of the netting (toward the tube sheet) with a baffle plate, curved to fit the cylindrical surface and covering just 120 degrees of the circumference. The reduction of the air passage to 40 sq. in. resulted in about the same reduction in flow as the difference between "plates all in" and "all out," respectively, in the first tests—the reduction ranging from 4 to 6

*See Bulletin 256, page 122.

per cent. The results of the tests with the cylinder of netting are plotted in Fig. 7.

14. *Measure of Resistance.*—It is possible to develop a convenient coefficient of resistance which is applicable to the model in the different states. If the relation between the draft d (in front of the diaphragm where one is used) and the hourly rate air flow W_a is plotted, this relation always takes the form indicated by the equation

$$W_a = Q \sqrt{d}$$

where Q , a coefficient experimentally determined, is invariable for any given front-end arrangement, no matter what nozzle is used. For the original arrangement, with all of the baffles in place, the value of Q is found to be 2050; with the damper, plate, netting and apron removed, 2130; with all of the plates removed, 2200. Lowering the nozzle in the empty front end has the effect of further increasing Q to 2300, and when the netting and baffle plate are placed around the base of the stack the coefficient again becomes 2200.

The coefficient Q as a measure of resistance is somewhat analogous to the quantity "temperament" of the gas passages as used by Legien in his analysis of front-end action (see Bulletin 256, page 33). The scale factors between prototype and model in the present investigation show that Q for the prototype should be 16 times as great as that for the model.* Hence for a comparable locomotive, values of 32 000 to 36 000 would be expected. In Bulletin 220 of the Engineering Experiment Station is a report of a series of tests on a 2-8-2 locomotive of the Illinois Central, and for the four rates of combustion in the tests without the thermic syphons the values for the quantity Q range from 25 000 to 25 900.† The variation from the figure suggested by the model bears out the statement made in Bulletin 256 that the resistance of the model was not made large enough to give perfectly quantitative results in the main series of tests. The value of Q could be calculated for any locomotive for which tests giving the rate of steam discharge, firing rate, and flue gas analysis are available, since from the latter the amount of products of combustion moved per hour by the front end can be calculated. This value of Q should be constant for any given front-end arrangement, except for the variation in the resistance of the fuel bed.

*The scale factor being 4, the amount of gas moved per hour is 4^3 as much in the prototype as in the model; the draft is 4 times greater in the prototype, hence since $Q = W_a \div \sqrt{d}$ the factor for the prototype is $4^3 \div 4^{\frac{1}{2}} = 16$.

†See Appendix C for calculations.

(B) Effect of Lowering Nozzle

15. *Critical Dimension.*—The importance of adequate stack height is thoroughly understood. With the development of large locomotives it was discovered that the necessary height could be obtained by extending the stack downward into the smokebox, if the nozzle were lowered at the same time. That is, the dimension of real importance is the distance from the top of the nozzle to the top of the stack. For convenience this dimension will be called $F + H$, F representing the distance from the top of the nozzle to the bottom of the stack flare, and H the height of the stack.

16. *Limitations.*—In the conventional type of front end, using a table plate as in Fig. 1, the value of $F + H$ must be determined by a compromise. A large value requires a low table plate, which in turn constricts the gas passage through the front end. The difficulty has been met in part by the following modifications in design:

- (a) Making the table plate partly of netting
- (b) Making the center of the plate lower than the sides
- (c) Depressing the top of the nozzle below the table plate, in a pocket
- (d) Coring out the top of the cylinder saddle to provide additional gas passage under a low table plate

Of these, (a), (b), and (d) are all effective, but the indications of the previous investigation were that, if the top of the nozzle were depressed below the top of the table plate, the pocketing canceled whatever gain there might be from lowering the nozzle. The remedy (d) may unduly increase the opening in the bottom of the smokebox sheets, and the size of the saddle; (b) if carried to extremes will result in a pocketing effect on the nozzle; (a) in part counteracts the effect which is desired when the plates are put in.

In the present investigation, after the plates had been removed from the front end as described in the previous section, the nozzle was lowered three inches by reducing the height of the stand. As originally arranged with a nozzle $1\frac{3}{4}$ inches high the distance $H + F$ was $17\frac{3}{4}$ inches, and by the lowering of the nozzle it was increased to $20\frac{3}{4}$ inches. A still greater distance was secured by the use of the $1\frac{5}{8}$ D nozzle (see Fig. 3), bringing the maximum to $22\frac{3}{4}$ inches. Tests were run with the standard Y nozzle, with the D, identical as to size and form of steam passage, also with the $1\frac{5}{8}$ L nozzle and the 4-hole pepperbox, raising and lowering the nozzles on rings from the upper limiting position to the lower limiting position. The distance F was

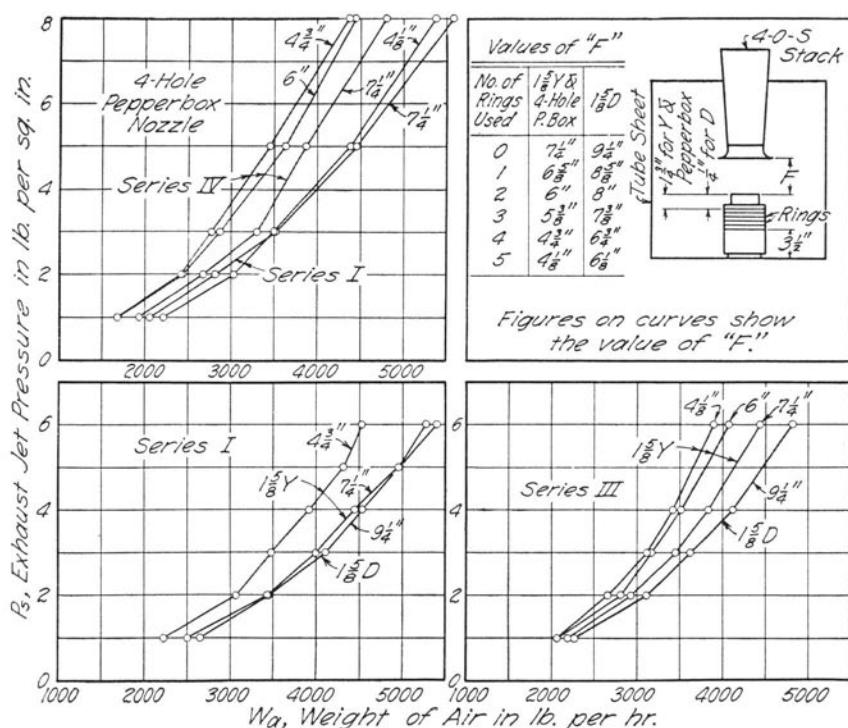


FIG. 8. EFFECT OF LOWERING NOZZLE

thereby varied from $4\frac{1}{8}$ inches to $9\frac{1}{4}$ inches, for the two nozzles $1\frac{5}{8}$ " Y- $1\frac{5}{8}$ " D considered together, and from $4\frac{1}{8}$ to $7\frac{1}{4}$ inches for the pepperbox. These tests were made on the 4-0-S stack, and also four modifications of this stack (all having different flare arrangements as will be shown in the following section) in an attempt to find out, if possible, whether there might be some specially outstanding combinations of F and flare. For the purpose of showing the effect of lowering alone, the tests with the 4-0-S stack are plotted in Fig. 8. The figure is in three parts, two referring to results secured by the use of the $1\frac{5}{8}$ " Y-D combination, and the third to results from the pepperbox nozzle. The laboratory work for this part of the investigation was run at four different times, under a wide range of operating conditions, such as extreme heat, relatively low steam pressure on the power plant line, etc., so that the results have been plotted by series, designated as I, III, IV (Series II not entering this comparison). Series-to-series comparisons are not accurate, but conditions

through each series remained constant and comparisons of results within each series are valid.

The effect of the change of F alone is seen in an improvement of about 12 per cent for the $1\frac{5}{8}$ Y-D tests, corresponding to a change in the dimension $F + H$ of 28 per cent. In the case of the pepperbox nozzle the change is much less, though still marked, especially in Series IV. Here there are two conflicting conditions: this nozzle shows a certain amount of cross-fire* effect at the larger values of F , hence in lowering the nozzle the inherent benefit derived from this process is discounted by the increasing cross-fire effect. There will be a value of F giving the best performance beyond which a further increase might be expected to result in a complete collapse. In Series I it would appear as if the $7\frac{1}{4}$ -inch value of F had about attained the maximum. Of course this general principle will hold with any nozzle, but in the case of those having compact jets, such as the plain round nozzle, the performance would not be liable to injury through cross-fire effect in any reasonable front-end design.

(C) Effect of Various Forms of Stack Bases

17. *Previous Conclusions.*—In the investigation reported in Bulletin 256, it occasioned considerable surprise that the results of tests with a given nozzle and stack body should be so little affected by variation in the form of the stack base, though this was in harmony with the wide variation in conclusions reached by previous experimenters in the field. As a check on the results previously obtained it was determined to make, in this supplementary investigation, a special study of the matter. Throughout Series II, the portion of the laboratory work devoted to this part of the investigation, weather conditions remained remarkably constant, and there was no variation in arrangement of instruments or calibrations, or other change that would confuse results in the slightest degree. For the purpose of this portion of the work six nozzles were used: three with compact jets ($1\frac{5}{8}$ Y, $1\frac{5}{8}$ D, and $1\frac{5}{8}$ L), two with moderately spreading jets, the 4-hole and 6-hole pepperboxes, and one with rather a wide-spreading jet, the star nozzle, made for the purpose. All of the three round-opening nozzles had the same diameter, 1.625 in. and an area of 2.08 sq. in.; the star nozzle had three superimposed slots each 2.06 by 0.37 inches, giving exactly 2.08 sq. in. area; the six-hole pepperbox had six $\frac{5}{8}$ -inch circular openings and a total area of 1.84 sq. in., while the

*By cross-fire effect is meant the striking of the flare of the stack by some of the steam from the nozzle. This steam seems, in effect, to rebound into the stream of steam and air, thereby reducing the efficiency of the air-entraining action.

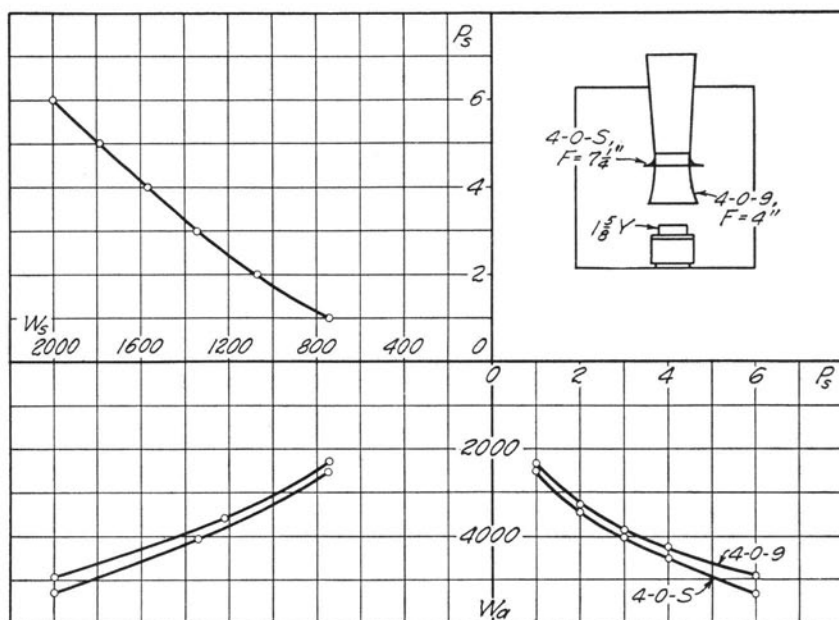
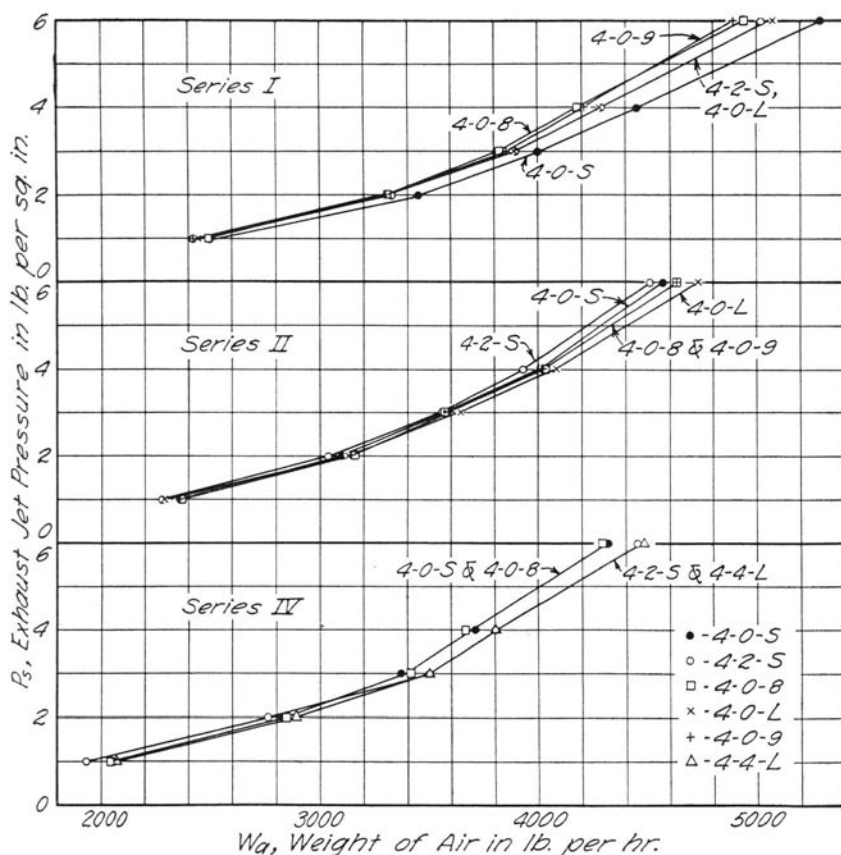


FIG. 9. EFFECT OF CHANGE IN FORM OF STACK FLARE

4-hole pepperbox had 4 circular openings of $\frac{3}{4}$ -inch diameter and an area of 1.77 sq. in. The nozzles are illustrated in Fig. 3, and the discharge rate for each for the range of pressures used is given in Appendix B. The No. 4 or 4-0-S stack was used, with four modifications in the base or flare, resulting in the 4-0-L, 4-0-8, 4-0-9, and 4-2-S.* In the 4-2-S the standard small flare was merely lowered by the insertion of a two-inch cylindrical extension; the "L" flare was of the same shape as the "S," but of larger diameter; the "8" was a long, conical skirt extending well down over the nozzle, and the "9" was a moderately long parabolic form. All are illustrated and dimensioned in Fig. 4.

18. *Tests with Various Stack Bases.*—The results of the tests are presented in a series of six figures, Figs. 9 to 15. Each of these is divided into two or more parts, depending on the number of series in which tests on this nozzle were run, since checking tests were run in the other series, as well as the main group of determinations in

*These stack designations indicate the form of the stack by three symbols (•)-(•)-(•), the first character showing the form of the stack, which is 4 in all cases in the present report; the second symbol indicates the length of cylindrical extension used, and the third symbol shows the form of the base. Figures 4A-4G show the shapes and dimensions for all of the stacks used.

FIG. 10. EFFECT OF CHANGE OF STACK FLARE, WITH $1\frac{5}{8}$ Y NOZZLE

Series II. In Fig. 9 the full plot, as shown in Fig. 5a, is presented for the $1\frac{5}{8}$ Y nozzle, and the widest range of results found for the stack-base variation, that is, the results for the 4-0-S and 4-0-9 stacks. The addition of the results for the other bases could have been made, but the drawing of separate air-flow curves would have been confusing. Later figures show the P_s - W_a plot only, with the air-flow scale exaggerated in order to show as well as may be the small differences in performance that are found.

In Fig. 10 the result of the tests with the $1\frac{5}{8}$ Y nozzle are shown for three series of runs. These exhibit minor differences in the order of merit of performance of the various stack bases, but nothing to modify the previous conclusion that, for a nozzle with a compact jet, the differences resulting from changes in the stack base were

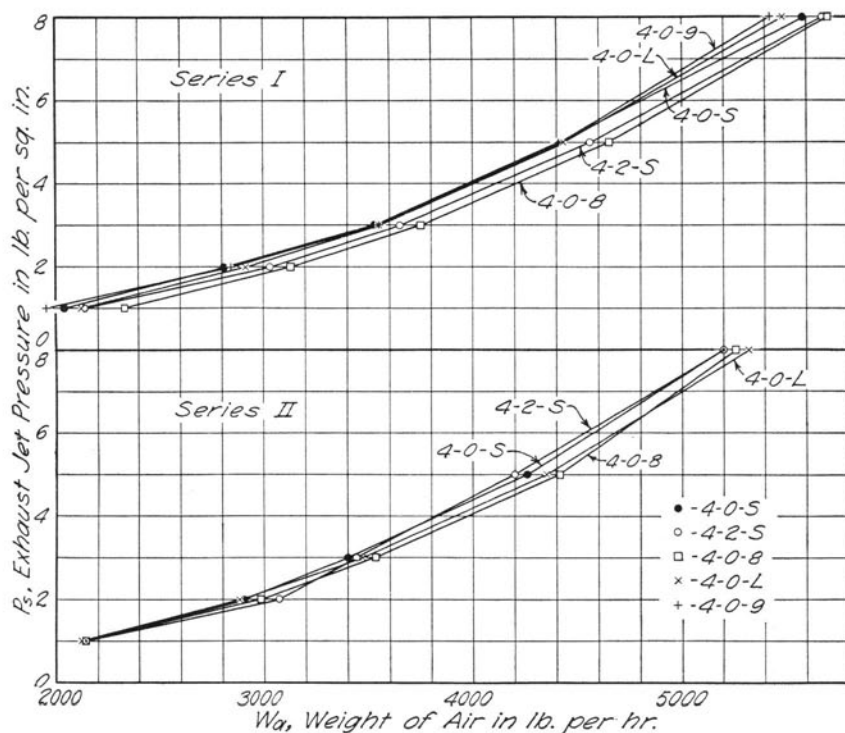


FIG. 11. EFFECT OF CHANGE OF STACK FLARE, WITH 4-HOLE PEPPERBOX NOZZLE

trifling and rather inconsistent. On account of the larger number of runs involved, precedence should be given to the results of the second series, in which there is a difference of only about 250 lb. of air moved per hour at the highest output. The No. 4 or 4-0-S stack is in the middle of the range, the 4-2-S giving a lower efficiency by an insignificant amount, and all of the large flare stacks show slight improvement on the performance of these two. In Fig. 14 are shown the strictly analogous effects which would be expected to result from the use of the $1\frac{5}{8}$ D nozzle. For the $1\frac{5}{8}$ L nozzle, the added length of the 4-2-S combination proved of some advantage at the highest rate of steam flow, as shown in Fig. 15. In Fig. 11, the results of the tests with the 4-hole pepperbox are shown. In the first series the use of the larger flare stacks seems to show a slight tendency to reduce the cross-fire effect and hence to improve performance, but in Series II the margin of difference in air flow resulting from variation in the stack base is too small to warrant drawing definite conclusions. The same

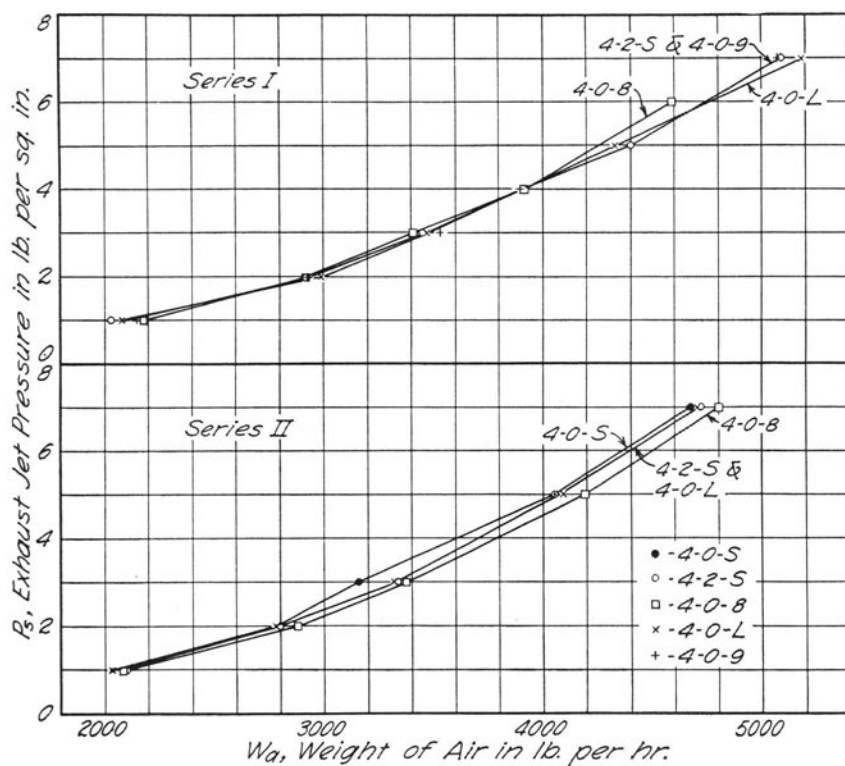


FIG. 12. EFFECT OF CHANGE OF STACK FLARE, WITH 6-HOLE PEPPERBOX NOZZLE

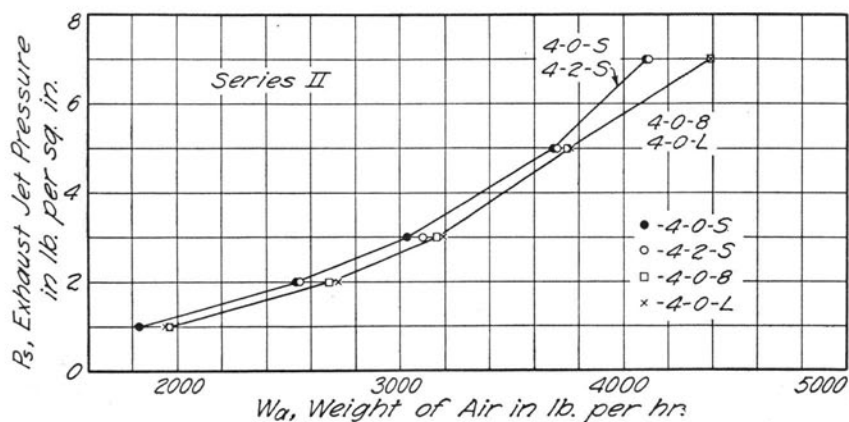
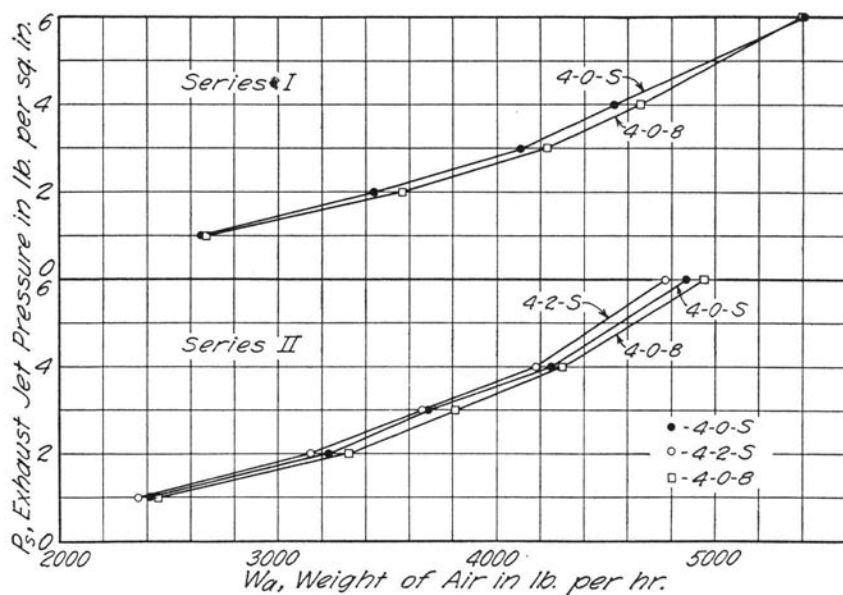
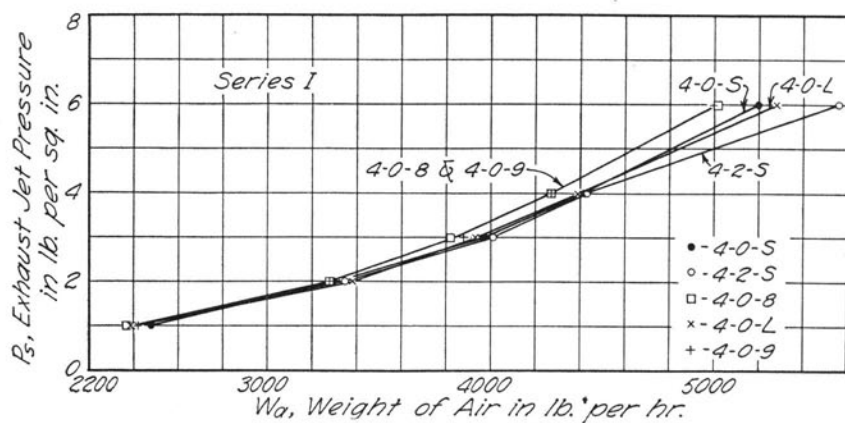


FIG. 13. EFFECT OF CHANGE OF STACK FLARE, WITH STAR NOZZLE

FIG. 14. EFFECT OF CHANGE OF STACK FLARE, WITH $15\frac{3}{8}D$ NOZZLEFIG. 15. EFFECT OF CHANGE OF STACK FLARE, WITH $15\frac{3}{8}L$ NOZZLE

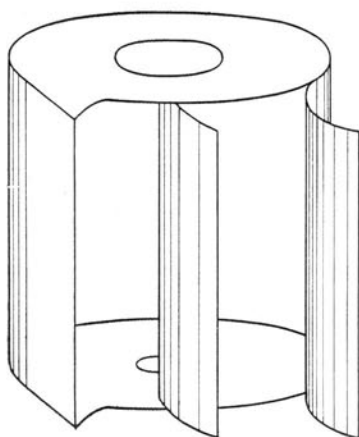


FIG. 16. GYRATORY SPARK ARRESTER

may be said of the performance resulting from the use of the six-hole pepperbox, as shown in Fig. 12. The star nozzle, Fig. 13, spreads the jet of steam quite widely, and consequently the wider flares show some advantage, the improvement being of the order of six per cent.

19. *Conclusions.*—In conclusion it may be stated that the general results of the earlier investigation, with regard to the effect of variation in the form and height of the base of the stack, have been very definitely confirmed by the supplementary investigation. The conclusions previously expressed were, in brief, that as long as there is no cross-fire effect, or actual loss of the steam beyond the rim of the flare, any reasonable shape for the base of the stack gives about as good results as any other, with a slight advantage accruing to the larger flares as the value of F is increased. For spreading jets where cross-fire effect may be anticipated, there is a slight advantage for the longer and wider flares.

(D) Gyratory Spark Arrester

20. *Description.*—This type of arrester, as illustrated by the "Cyclone" type now being marketed, consists of a drum surrounding the base of the stack and the nozzle. One side of this drum, about 150 degrees, is open for the entry of the combustion gases and cinders; vanes are provided to lead these into the drum and to give them rotary motion within the drum after their entering. This rotation throws the cinders outward, either breaking them up to a degree which renders them safe for ejection through the stack, or delivering them

to hoppers whence they may be returned to the firebox. The netting is eliminated. The drum is applied with its open end either toward the front of the smokebox, or toward the tube sheet. The arrangement of the arrester is shown in Figs. 4I and 4J, and the drum as built for the model is shown in Fig. 16.

21. *Tests of Model Gyratory Spark Arrester.*—The drum built for the model was practically 13 inches high and 12 inches in diameter, and was applied after the lowering of the nozzle. It was used with the opening toward the front end and also toward the tube sheet, and tested with six different nozzles. The first group of determinations was made with the opening toward the front of the smokebox. When so arranged the net passage for the air around the arrester was 204 sq. in., as compared with a minimum of 73 sq. in. under the apron in the original arrangement. However, much of the 204 sq. in., if utilized, represents a long and tortuous path for the air; but the combined areas of the more direct paths around the sides and below the drum is still greater than the 73 sq. in. of the Master Mechanics' arrangement. The extension of the stack inside the drum was such that there would be a dead-air pocket above the flare; these conditions suggested that a best position for the drum might be found by raising or lowering it by means of rings placed on the nozzle stand. As a result of such trials the performance with one ring on the stand was found to be very slightly better than that without the ring, and much better than that obtained with two rings. The one-ring arrangement was consequently adopted as standard for tests in which the opening of the arrester was turned away from the tube sheet.

Tests on the gyratory arrester were run in each of the three series, I, III, and IV, previously referred to, with arrangements as follows:

Series I: Tests were run with the arrester open toward the front end of the boiler (boiler head) and also with the arrester open toward the tube sheet; six different nozzles were used for each arrangement, and, in the case of the opening toward the boiler head, some trials were made with vertical variation in the position of the arrester relative to the nozzle stand.

Series III: Tests were run with the 1 $\frac{5}{8}$ Y and 1 $\frac{5}{8}$ D nozzles with the arrester open toward the front (away from the tube sheet).

Series IV: Tests were run with the arrester open both ways, using the 1 $\frac{5}{8}$ Y and the 4-hole pepperbox nozzles.

22. *Results of Tests.*—In Fig. 17 the results obtained in the Series I tests are shown; each of the six parts of this figure corresponds to

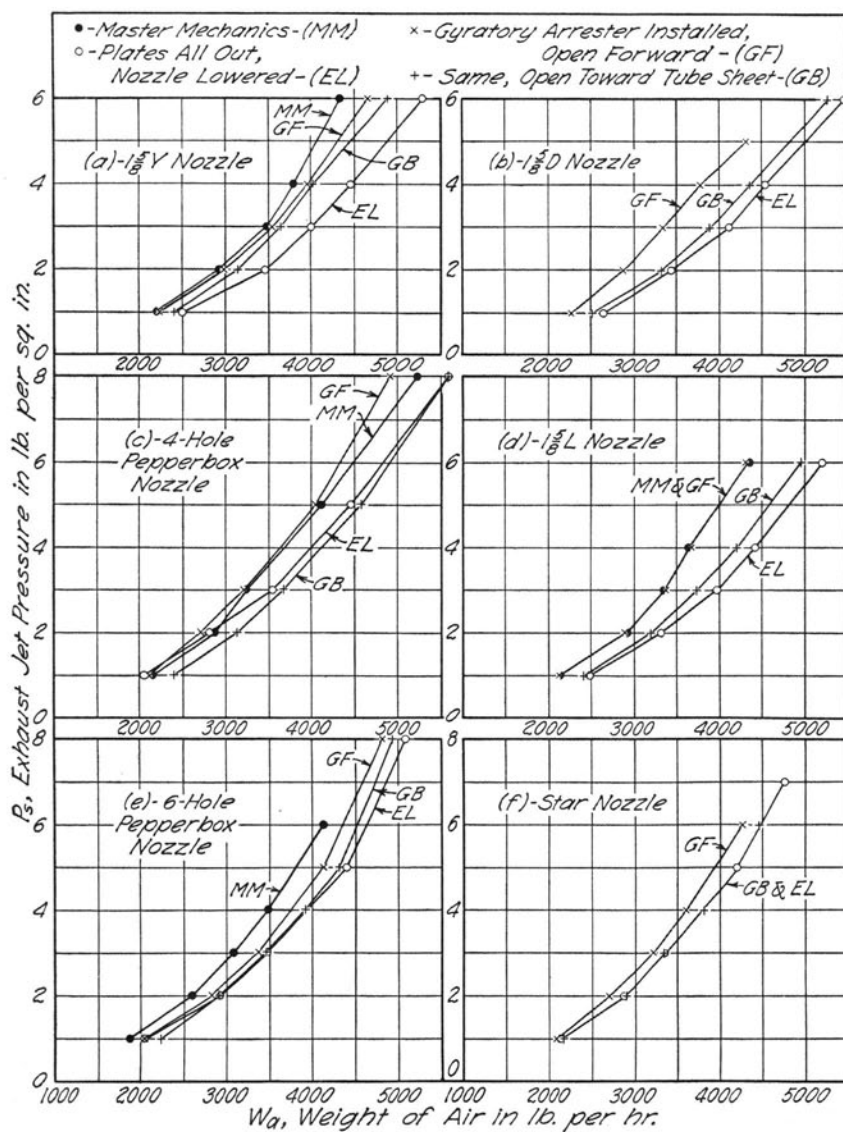


FIG. 17. TESTS WITH GYTRATORY SPARK ARRESTER

one of the six nozzles used, four front-end arrangements being used with each nozzle except the $1\frac{5}{8}$ L and the star, which were tried with three arrangements only. The front-end arrangements used were as follows:

The original Master Mechanics' arrangement with plates and netting, hereafter referred to for brevity as "MM"; this is illustrated in Figs. 4A and 4B.

The empty front end with the netting and all plates removed, and with the nozzle lowered 3 inches as shown in Fig. 4C, referred to here as "EL."

The empty front end fitted with gyratory arrester with the opening away from the tube sheet, shown in Fig. 4I, and referred to as "GF."

The same, except that the opening of the arrester was turned toward the tube sheet, as in Fig. 4J, referred to as "GB."

The improvement resulting from the change of arrangement from MM to EL has already been discussed under the headings "Effect of Reducing Front-End Resistance" and "Effect of Lowering Nozzle." This improvement, in terms of air flow for a given steam discharge with a given nozzle, is very considerable, ranging up to about 18 per cent. It must be borne in mind, however, that arrangement EL is not actually practicable, since some means of breaking up the sparks before their discharge is essential, but the results obtained from this arrangement serve well as a limiting figure for comparison purposes. Arrangement GF, in general, gives a little better results than arrangement MM; arrangement GB further improves on the results from GF, the results lying between those for GF and EL. Thus the normal order of merit, in order of the amount of air moved under identical conditions of steam discharge, is EL-GB-GF-MM, arrangement EL giving the largest air movement and arrangement MM the smallest. In the case of the six nozzles tested there is substantial agreement in this order. For the three round-opening nozzles, the empty-front-end-low-nozzle arrangement gives uniformly the best results; for the 4-hole pepperbox the results are second best, and for the 6-hole pepperbox and the star the results are substantially equal to the best, sharing the position with the arrester-open-toward-the-tube-sheet, GB. This latter arrangement gives the best results with the 4-hole pepperbox and the second best with the three round nozzles. All first and second positions are therefore held by EL and GB. The arrester-open-forward arrangement, GF, is definitely third best in two cases ($1\frac{5}{8}$ Y and 6-hole pepperbox); it shares the lowest rank in two cases ($1\frac{5}{8}$ L and

4-hole pepperbox); and it ranks third, necessarily, in the two remaining cases, since with the star and the $1\frac{1}{8}D$ the Master Mechanics' arrangement was not used. The foregoing statements as to order of performance may be summarized in tabular form as follows, an "equals" sign between two symbols indicating that there was no significant difference in the performance of the arrangements so represented; the sign "#" indicates the lack of any reliable test data for the arrangement designated.

Nozzle	Order of Performance				
	1 (best)	2	3	4 (poorest)	
$1\frac{1}{8}Y$	EL	GB	GF	MM	
$1\frac{1}{8}D$	EL	GB	GF	#	
$1\frac{1}{8}L$	EL	GB	GF	=	MM
4-hole pepperbox.....	GB	EL	MM	=	GF
6-hole pepperbox.....	EL =	GB	GF		MM
Star.....	EL =	GB	GF		#

The most striking thing about this comparison is the reversal of the usual order for the 4-hole pepperbox. However, the results obtained from the two pairs EL-GB and GF-MM, respectively, will be seen to lie so closely together that the general conclusions are not affected. All tests of the EL arrangement were run with the 4-0-S stack except those for the star and 6-hole pepperbox, where the 4-2-S stack was used. There is so little difference resulting from the use of these two stacks that the comparison remains valid.

23. Conclusions.—All of the tests used in these comparisons were made as part of the work of Series I. The tests of Series III and IV were mainly run as a check on those of the first group. The later tests fully confirmed conclusions drawn from the earlier series: if there were differences in the results, they were somewhat in favor of the gyratory arrester, tending to bring the results closer to the values obtained with the empty front end. In view of the reduction of air flow caused by the presence of a netting, as shown earlier in this chapter and summarized in Fig. 7, the results given by the empty front-end arrangement EL are from 5 to 7 per cent better than can be obtained in practice, hence, in every case of the six, the results from the arrester open toward the tube sheet GB are actually as good as or better than those which could be obtained with EL modified by a netting and baffle plate. Further it is evident that the arrester gives consistently better results with the opening toward the tube sheet, though part of the improvement may be due to the removal of the ring on the nozzle stand which is necessary in the other arrangement, and the consequent increase in the distance between the top of the nozzle and the top of the stack.

(E) Eccentric Nozzle

24. *Bending of Steam Jet.*—In Bulletin 256 there was recorded the observation of the bending of the jet away from its normal axis, due to the impingement of the stream of air flowing through the netting. In the present investigation, after the netting and baffle plate were removed and impingement was from the rear, a forward-bending effect was expected. That this actually occurred could be seen from the side of the model after the nozzle had been lowered, and it was also apparent from the varying wetting of the stack base when the steam was first turned on and the model still cold. Under these conditions, the problem arose as to whether the best performance was to be secured with the nozzle in its traditional position on the axis of the stack, or with the nozzle moved slightly so as to bring the center of the jet at the height at which it entered the stack more nearly on the stack axis.

25. *Tests with Eccentric Nozzle.*—As a means of studying this effect, the $1\frac{1}{2}$ W nozzle of the previous investigation was provided with slots in place of stud holes for attaching it to the nozzle stand, the slots being cut a little over an inch long. The nozzle has a height of $1\frac{3}{4}$ inches, with a cylindrical bore, $1\frac{1}{2}$ inches in diameter both at top and bottom, and slightly chamfered on the bottom. The steam discharge for the usual range of pressures for this nozzle appears in Appendix B. The 4-0-S stack was used, and tests were first run with the nozzle centered exactly under the stack base. After this the nozzle was moved successively $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{5}{8}$ inch forward, and also by the same steps backward of the axial position, and runs were made for each position. The base of the nozzle being practically only $1\frac{1}{2}$ inches in diameter, and the opening in the exhaust stand 2.52 inches, any displacement further than $\frac{1}{2}$ inch in either direction tends to constrict the steam passage, and the results are not quite comparable with those for full steam discharge.

26. *Results of Tests.*—In Fig. 18 are plotted the results in terms of air flow per hour for various steam pressures for five positions of the nozzle, central, and $\frac{1}{4}$ and $\frac{1}{2}$ inch eccentric each way. The extreme positions are not plotted for the reason stated in the preceding paragraph. In these extreme positions, the performance “collapsed”—the front end filled with steam and the air flow dropped 30 per cent for the forward position and 15 per cent for the back position. These reductions compare with a possible loss of steam flow of about 5 per cent. For the five positions plotted, it will be seen that the

best results were found when the nozzle was set one-fourth inch back of the stack axis, and that the slopes of the curves would indicate that a slightly better value might have been obtained at say 0.18 or 0.20 inch backward displacement. Attempts to obtain an exact maximum, however, were unsuccessful. The best performance obtained, at each rate of discharge, was about 2 per cent better than that for the axial position of the nozzle. An eccentricity of $\frac{1}{4}$ inch, forward, was effective in reducing the performance as much as or a little more than an eccentricity of $\frac{1}{2}$ inch backward.

27. *Conclusions.*—In Bulletin 256, attempts to measure the backward bending of the jet from a $1\frac{1}{2}$ -inch nozzle indicated that the axis of the jet was displaced $\frac{1}{4}$ inch as it entered the base of a stack, where F was 8 inches. In the present case F was $7\frac{1}{4}$ inches, and a displacement of the axis of 0.2 inch (in the ratio of the squares of the respective F 's) would be expected. The agreement of this figure with the position of the nozzle which resulted in the best performance is of interest. The data in general point out the seriousness of an error in locating the nozzle if the error moves the nozzle *away* from the impingement side, and that a movement *toward* the impingement side is actually beneficial.

IV. SUMMARY AND APPLICATION TO FULL-SIZE LOCOMOTIVE

28. *General Relation Between Model Investigation and Locomotive Practice.*—In the foregoing pages, the study of five sets of conditions has been reported, and each condition represented a method of improving the draft performance of a locomotive which is being hopefully experimented with at the present time. As in the earlier investigation of Bulletin 256, every conclusion reached on the basis of the showing of the model data corresponds closely to what meager information is available from locomotive tests, and there is no reason for hesitating to infer that the model results are, *in toto*, qualitatively applicable to the locomotive. The five conditions of the investigation will be summarized serially.

29. *Reduction of Front-End Resistance and Lowering of Nozzle.*—The so-called Master Mechanics' front end draws the products of combustion and the excess air through the tubes and ejects them from the stack by a tortuous route through the front end which represents the equivalent of five right-angle turns. This form of front end is not found necessary outside of North America; elsewhere the general

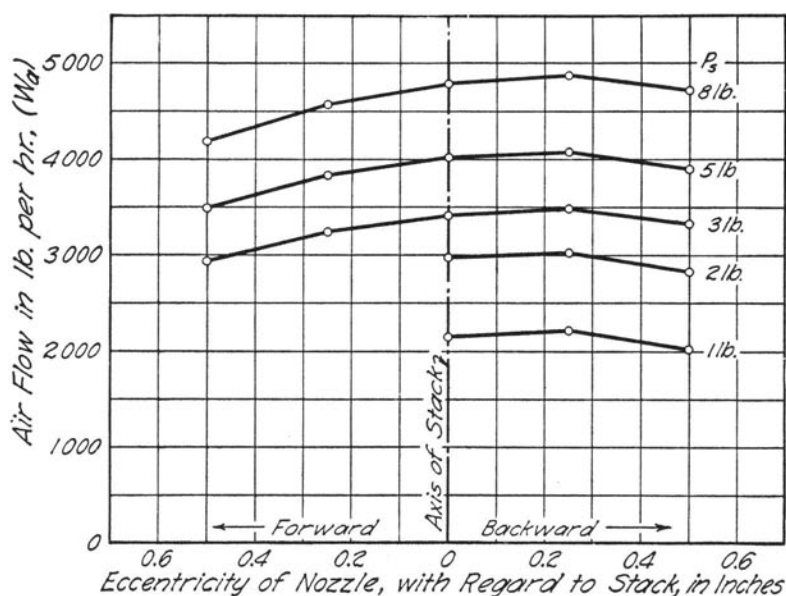


FIG. 18. EFFECT OF ECCENTRICITY OF NOZZLE AND STACK

course of the gases is represented by a single upward turn from the flues through the stack. Such an arrangement used with American coal would require the presence of at least an adequate netting to reduce the size of the sparks to a safe degree. If the sparks can be so reduced without greatly increasing the resistance, a small improvement in performance over the usual front-end arrangement results. In addition to this small improvement, an important accessory advantage results from the removal of the front-end plates, and particularly the table plate and the restricted air passage below it, since it permits a considerable lowering of the nozzle. This in itself represents a more important gain than the removal of the plates. Improved performance means drawing through the firebox, tubes and front end a larger amount of air for a given nozzle, steam pressure and steam discharge. Consequently, if such an improvement is made in a locomotive which was already steaming well, the necessary air requirement for the same rate of steam discharge can be met by reducing the velocity of the discharge—that is, by increasing the nozzle opening. The combined gain in air flow due to removal of the plates and lowering the nozzle was of the order of eighteen per cent for nozzles with compact jets, and twelve per cent for those with spreading jets. For a given rate of steam

discharge, the air flow is measured by a quantity $k_1V + k_2$, where k_1 and k_2 are experimental constants and V is the mean velocity of discharge; the two terms of the expression are of about equal importance. Hence a decrease in steam velocity would reduce the air flow in a lower ratio than that of the velocity reduction, and a small reduction in air flow requirement would permit a material increase in nozzle opening, with the corresponding advantage of reduced exhaust pressure.

30. *Form of Stack Base.*—With nozzle and stack heights fixed within close limits, unless a general reconstruction or redesign of the front end is planned, experimentation with the form and height of the stack base has been an inviting means of attempting to improve draft performance. Such experimenting has resulted in wide differences in arrangement, and in opinions with regard to the respective merits of each. The work of previous model experiments left the question in confusion, but the combined conclusions of the main part of the present investigation recorded in Bulletin 256 and of the supplementary work reported herein are that there is very little chance for improvement due to such changes unless

- (a) the bottom of the flare is so low that there is a constriction of the gas passage into the base of the stack; or
- (b) the flare is so related to the nozzle in form and position that there is an important cross-fire effect.

Both of these conditions call for obvious remedies, but otherwise the similarity of the results obtained from the use of stack bases varying widely both in form and height indicates that there is little to be hoped for from such experiments.

31. *Gyratory-Type Spark Arrester.*—Repeated testing of the gyratory arrester as built for the model showed that the amount of air moved by a given steam jet was greater than that for the Master Mechanics' front end, and less than that for the ideal empty front end with the low nozzle. It was comparable with the results secured by the use of the simplest possible form of cylindrical netting and baffle plate arrangement which might be expected to break up the sparks adequately. The performance is improved by shortening and removing U turns from the gas passages traversed before entering the arrester.

32. *Centering Nozzle Under Stack.*—Great emphasis has been placed on centering the nozzle in locomotive maintenance, and much

bad front-end performance has been charged to the fact that the nozzle was found to be off-center. In the Master Mechanics' front end, if the nozzle is off-center backward, the results would unquestionably be rather serious. On the other hand, for a slight eccentricity ahead of the stack axis—one-half or three-quarters of an inch for the usual range of F values—the results would probably be definitely advantageous.

APPENDIX A

SUMMARY OF FRONT-END ARRANGEMENTS TESTED

In the following Table 1 are listed 60 different arrangements on which 760 determinations were made. The centering tests made on the 1½W nozzle are not included in this table.

TABLE 1
FRONT-END ARRANGEMENTS TESTED

Stack	General Arrangement	Nozzle											
		1½ Y With number of rings shown					4-Hole Pepperbox With rings as shown			1½ L	1½ D	6-Hole Pepper- box	Star
		0	2	3	4	5	0	2	4				
4-0-S	Plates all in place.....	71	...	...	...	...	11	...	...	20	...	12	...
	Netting and diaph. re- moved.....	31	...	...	...	...	11	...	...	13	...	11	...
	All plates removed.....	20	...	...	...	...	14	...	...	5	...	...	6
4-0-S	All plates out, nozzle lowered.....	51	15	5	5	10	15	5	5	15	30	5	10
4-0-8	No netting.....	26	...	...	...	...	12	...	...	5	...	10	10
	With netting.....	5	...	...	...	...	...	...	...	...	...	...	...
	With netting and baffle.....	5	...	...	...	...	...	...	...	...	...	...	...
4-0-L	No plates, low nozzle.	15	...	...	...	...	5	...	...	5	...	5	5
4-0-9	No plates, low nozzle.	15	...	...	...	...	5	...	...	5	...	6	5
4-2-S	No plates, low nozzle.	25	...	...	...	...	10	...	...	15	...	10	5
4-4-L	No plates, low nozzle.	5	...	...	...	...	...	...	...	...	...	...	...
4-0-S	Cyclone, open forward	37	10	...	...	...	15	...	...	10	15	5	5
	Cyclone, open backward	16	...	...	...	...	13	...	...	5	5	5	5

The numbers in the spaces indicate the number of determinations made in each case.

APPENDIX B

STEAM DISCHARGE FOR NOZZLES USED IN TESTS

The accompanying Table 2 shows the steam discharge for each of the seven nozzles used in this supplementary series of tests, for the range of pressures used. The source of the figures presented is as follows:

1 $\frac{5}{8}$ Y	} From steam meter readings, previous investigation.
4-hole pepperbox	
1 $\frac{1}{2}$ W	
1 $\frac{5}{8}$ D	
1 $\frac{5}{8}$ L	The size and shape of this nozzle are identical with those of the 1 $\frac{5}{8}$ Y, hence discharge will be identical.
	Same as 1 $\frac{5}{8}$ Y in top and bottom diameters, but due to lower height, the slope of the walls is more abrupt. This nozzle bears a relation to the 1 $\frac{5}{8}$ Y similar to that the Q1.5L nozzle of the previous investigation bore to the 1 $\frac{1}{2}$ Y, and the same reduction in steam flow (4 to 6 per cent) is used to determine the flow for the 1 $\frac{5}{8}$ L as was found for the Q1.5L.
6-hole pepperbox	The area is 4.2 per cent greater than that for the 1 $\frac{1}{2}$ Y; the discharge rate for the 4-hole pepperbox is 5.5 per cent less than for the 1 $\frac{1}{2}$ Y, hence the discharge for the 6-hole pepperbox is taken as 1.3 per cent less than that for the 1 $\frac{1}{2}$ Y, which is known from the steam meter measurements of the previous investigation.
Star	Area exactly equal to that of the 1 $\frac{5}{8}$ Y. Taking into consideration the relation found for other nozzles between area and perimeter, it was estimated that the steam discharge for this nozzle would be 18 per cent less than that for the 1 $\frac{5}{8}$ Y. The results are almost identical with those for the 6-hole pepperbox, and the sound and vibration resulting from the use of this nozzle as compared with the pepperbox made it evident that the estimate was fairly correct.

TABLE 2
STEAM DISCHARGES AT VARIOUS PRESSURES FOR ALL NOZZLES USED

Nozzle	Pressure in Throat of Jet, lb. per sq. in.							
	1	2	3	4	5	6	7	8
	Steam Discharge, lb. per hr.							
1 $\frac{5}{8}$ Y and 1 $\frac{5}{8}$ D.....	750	1070	1340	1570	1790	2000	2200	2400
1 $\frac{5}{8}$ L.....	730	1030	1290	1510	1720	1900	2090	2280
4-hole pepperbox.....	590	860	1070	1250	1410	1580	1730	1850
6-hole pepperbox.....	640	940	1140	1330	1480	1640	1810	1980
Star.....	620	880	1100	1290	1460	1640	1810	1980
1 $\frac{1}{2}$ W.....	660	980	1180	.....	1540	.....	.....	1940

The figures in the table show the steam discharged in pounds per hour for the given nozzle at the specified pressure. The steam as discharged was superheated from 5 to 11 deg. F.

APPENDIX C

CALCULATION OF RESISTANCE COEFFICIENT "Q"

The data appearing in lines 1, 2, 3, 4 and 6 of Table 3 are taken from the reports of a series of tests on a locomotive with and without thermic syphon equipment, as reported in Bulletin 220 of the University of Illinois Engineering Experiment Station. The figures shown are the averages for the accepted tests at each of the four rates of working, for the locomotive without the syphons.

TABLE 3
CALCULATION OF RESISTANCE COEFFICIENT "Q"

Item	Rate of Combustion			
	Low	Second	Third	High
1. Air per pound coal as fired, lb.....	14.76	13.85	13.14	11.16
2. Coal fired per hour, lb.....	2510	3650	5510	7010
3. Air per hour, lb.....	37,000	50,600	72,400	78,300
4. Cinder percentage.....	1.2	1.5	3.7	6.4
5. Products of combustion, lb. per hr.....	39,300	54,000	77,200	84,000
6. Draft in front of diaphragm, in.....	2.37	4.39	9.01	11.73
7. $Q = W_a \div \sqrt{d}$	25,600	25,800	25,700	24,900

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